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14. ABSTRACT An enumeration of several research efforts funded by the above award is attached. Key aspects reported on include: (a) Optically controlled delays for broadband pulses and all-optical beam steering; (b) Sub-wavelength atom localization; (c ) Quantum microscopy; (d) Quantum lithography with classical light; (e) Quantum entanglement: Measures and generation schemes					
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# **Quantum Optical Implementations of Quantum Computing and Quantum Informatics Protocols**

**AFOSR Grant No.: FA9550-05-1-0433**

**Final report**

**July 1, 2005 - May 31, 2006**

**Principal Investigators:**

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## ***I. Technical Status Report***

### **A. Research description**

During the funding period (July 1, 2005 - May 31, 2006) we carried out a number of studies in the field of quantum computing and quantum informatics in accordance with the tasks proposed in the project. Following is the summary of our research progress. The details can be found in our enclosed published and submitted papers.

#### **(a) Optically controlled delays for broadband pulses and all-optical beam steering:**

The recent progress in the study of ultra-short optical pulse generation creates a fundamentally new realm of laser applications in many areas, including material science, information processing, communication and spectroscopy. The fast developing technology of broadband optical pulse shaping requires systems to provide controllable delays for such pulses. For example, an optical buffer can be characterized by the maximum number of bits  $N$  that can be simultaneously stored in the buffer. In terms of the bit rate  $B$  and the pulse delay  $\tau$ , the number  $N$  is given by  $N = B\tau$ . The maximum bit rate is however given by  $B = 1/T$  where  $T$  is the pulse width related to the bandwidth of the system. Thus,  $N$  has a simple physical meaning: It is the ratio of the delay time of the buffer and the pulse duration and corresponds to the number of pulses that can be simultaneously processed by the buffer.

We showed that the steep dispersion of an electromagnetically induced transparency (EIT) medium can be used to create large controllable delays for ultra-short pulses by using the system discussed in [1]. In particular we showed that it is possible to produce a microsecond delay for 10 picosecond optical pulses, thus yielding a time-delay-bandwidth product of about  $10^6$ . The best product achieved so far in slow-light experiments is 3. An important feature of our scheme is that the delay is continuously controllable by an optical field. The idea is to synthesize dispersion of the system by using the highly steep dispersion of a three-level atomic system with inhomogeneous broadening. An alternate scheme is discussed in [2]

We also proposed a scheme that provides steering of the direction via all optical control [3]. The system is based on steep dispersion of coherently driven medium in which the electromagnetically induced transparency (EIT) occurs.

#### **(b) Sub-wavelength atom localization:**

High-resolution position measurements of the atom with optical techniques are of considerable interest, both from a theoretical, as well as from an experimental, point of view. The interest in the area is largely due to its applications to many areas of optical manipulations of atomic degrees of freedom, such as laser cooling, Bose-Einstein condensation, atom lithography and the measurement of the center of mass wave function

of moving atoms. It is well known that optical methods provide better spatial resolution in position measurement of the atom.

We proposed a scheme for sub-wavelength localization of an atom conditioned upon the absorption of a weak probe field at a particular frequency [4]. Manipulating atom-field interaction on a certain transition by applying drive fields on nearby coupled transitions leads to interesting effects in the absorption spectrum of the weak probe field. We exploit this fact and employ a four level system with three driving fields and a weak probe field, where one of the drive fields is a standing wave field of a cavity. We show that the position of an atom along this standing wave is determined when probe field absorption is measured. We find that absorption of the weak probe field at a certain frequency leads to sub-wavelength localization of the atom in either of the two half-wavelength regions of the cavity field by appropriate choice of the system parameters.

#### **(c ) Quantum microscopy:**

Precision measurement of small separations between two atoms or molecules has been of interest since the early days of science. We proposed a scheme which yields spatial information on a system of two identical atoms placed in a standing wave laser field [5,6]. The information is extracted from the collective resonance fluorescence spectrum, relying entirely on far-field imaging techniques. Both the interatomic separation and the positions of the two particles can be measured with fractional-wavelength precision over a wide range of distances from about  $\lambda/550$  to  $\lambda/2$ .

#### **(d) Quantum lithography with classical light:**

We showed how to achieve sub-wavelength diffraction and imaging with classical light, previously thought to require quantum fields [7, 8]. By correlating wave vector and frequency in a narrowband, multi-photon detection process that uses Dopplerson-type resonances, we show how to achieve arbitrary focal and image plane patterning with classical laser light at sub-multiples of the Rayleigh limit, with high efficiency, visibility, and spatial coherence. A frequency-selective measurement process thus allows one to simulate, semiclassically, the path-number correlations that distinguish a quantum entangled field.

#### **(e) Quantum entanglement: Measures and generation schemes:**

We provide a class of inequalities whose violation shows the presence of entanglement in two-mode systems [9, 10]. We consider observables that are quadratic in the mode creation and annihilation operators and find conditions under which a two-mode state is entangled. Further examination allows us to formulate additional conditions for detecting entanglement. We also show how the methods used here can be extended to find entanglement in systems of more than two modes.

We have also examined schemes for the generation of macroscopic fields that are entangled [11, 12]. These schemes may be useful in quantum communication protocols.

## B. Papers published/submitted

During the report period, the following papers were published / submitted:

1. ``Optically controlled delays for broadband pulses'', Q. Sun, Y. V. Rostovtsev, J. P. Dowling, M. O. Scully, and M. S. Zubairy, Phys. Rev. A **72**, 031802 (Rapid Communications) (2005).
2. ``Time-bandwidth problem in room temperature slow light'', Z. Deng, D.-K. Qing, P. Hemmer, C. H. R. Ooi, M. S. Zubairy, and M. O. Scully, Phys. Rev. Lett. **96**, 023602 (2006).
3. ``Optical beam steering based on electromagnetically induced transparency'', Q. Sun, Y. V. Rostovtsev, and M. S. Zubairy, Phys. Rev. A (in press).
4. ``Sub-wavelength localization of an atom via amplitude and phase control of the absorption spectrum-II'', K. T. Kapale, and M. S. Zubairy, Phys. Rev. A **73**, 023813 (2006).
5. ``Measurement of the separation between molecules beyond classical limit'', J. Chang, J. Evers, M. O. Scully, and M. S. Zubairy, Phys. Rev. A **73**, 031803 (Rapid Communications) (2006).
6. ``Distilling two-atom distance information from intensity-intensity correlation function'', J. Chang, J. Evers, and M. S. Zubairy, Phys. Rev. A (in press).
7. ``Quantum lithography with classical light'', P. R. Hemmer, A. Muthukrishnan, M. O. Scully, and M. S. Zubairy, Phys. Rev. Lett. **96**, 163603 (2006).
8. ``Quantum lithography with classical light: Generation of arbitrary patterns'', Q. Sun and M. S. Zubairy, Phys. Rev. A (submitted).
9. ``Entanglement conditions for two-mode states'', M. Hillery and M. S. Zubairy, Phys. Rev. Lett. **96**, 050503 (2006).
10. ``Applications of entanglement conditions for two-mode states'', M. Hillery and M. S. Zubairy, Phys. Rev. A (in press).
11. ``Single-atom as a macroscopic entanglement source'', L. Zhou, H. Xiong, and M. S. Zubairy, Phys. Rev. A **74**, 022321 (2006).
12. ``Influence of pump phase fluctuations on entanglement generation using correlated emission laser'', S. Qamar, H. Xiong and M. S. Zubairy, Phys. Rev. A (submitted).

### **C. List of professional personnel involved**

The following personnel participated in the research effort:

1. Marlan O. Scully, Distinguished Professor
2. M. Suhail Zubairy, Professor
3. Ashok Muthukrishnan, Post-Doctoral Fellow
4. Yaping Yang, Visiting Scientist
5. Juntao Chang, Graduate student
6. Qingqing Sun, Graduate student

### **D. Papers presented at meetings, conferences, seminars**

The results were presented at several conferences and lecture series. These include:

1. "Coherence induced entanglement", (Invited paper) at the SPIE Conference on Quantum Communications and Quantum Imaging III, held at San Diego, July 31-August 4, 2005.
2. "Coherence induced entanglement", (Invited paper) at KIAS-KAIST Workshop on Quantum Information Science, held at Seoul, Korea, August 22-24, 2005.
3. "Master equation approach to Bose-Einstein condensation" (Invited lecture) at the Princeton BEC Symposium, Princeton University, Oct. 14-15, 2005.
4. "Propagation of Broadband Pulse in EIT Medium", at the Annual Meeting of the Optical Society of America, Tucson, Arizona, Oct. 17-20, 2005.
5. "Quantum Entanglement: Measurement Criteria and Applications" (Invited talk) at the Symposium on Mathematics of Quantum Computation and Quantum Technology, Texas A&M University, November 13 - 16, 2005.
6. "Quantum computing: New frontiers", (Keynote speaker) at Saudi Physical Society Meeting, Mecca, Saudi Arabia, Nov. 27-29, 2005.
7. Quantum Entanglement: Microscopic and macroscopic", (Special lecture) at the King Khalid University, Abha, Saudi Arabia (Nov. 27, 2005).

8. “Atomic coherence and applications”, (Invited series of lectures) at The 13<sup>th</sup> APCTP-KIAS Workshop on Nanoscale and Mesoscopic Systems: Mesoscopics meets Quantum Optics, at the Pohang University of Science and Technology, Korea, Dec. 12-13 (2005).
9. “Correlated Emission Laser as an Entanglement Amplifier”, (Invited speaker) at the International Conference on Quantum Optics, Chinese University of Hong Kong, Hong Kong, China, Dec. 17-20 (2005).
10. “Quantum entanglement: microscopic and macroscopic”, (special lecture) at COMSATS Institute of Information Technology, Islamabad, Dec. 27, (2005).
11. “Coherent atomic interactions”, (special lecture) at COMSATS Institute of Information Technology, Islamabad, Dec. 29, 2005.
12. “All optical controlled steering of light” (Invited lecture) at the Conference on Advanced Optical and Quantum Memories and Computing III, in San Jose, California, Jan. 24-25 (2006).
13. “Time and quantum: Quantum eraser” (Invited lecture) at Wheelerfest, Princeton University, Feb. 24-25 (2006).
14. “Quantum interferometry: From quantum eraser to quantum microscopy and lithography”, (Invited lecture) at TAMU-Princeton Joint Seminar, May 19-20 (2006).